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'Opening up' geoengineering appraisal: Multi-Criteria Mapping of options for tackling climate change

Rob Bellamy[*a,b,c], Jason Chilvers[a,c], Naomi E. Vaughan[a,b], Timothy M. Lenton[d]

[*] Corresponding author. Tel.: 01603 591346; E-mail address: r.bellamy@uea.ac.uk.

[a] School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, UK.
[b] Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, UK.
[c] Science, Society and Sustainability (3S) Research Group, School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, UK.
[d] College of Life and Environmental Sciences, University of Exeter, Hatherly Laboratories, Prince of Wales Road, Exeter, EX4 4PS, UK.

Abstract

Concerted efforts have begun to appraise deliberate, large-scale interventions in the Earth's climate system known as 'geoengineering' in order to provide critical decision support to policy makers around the world. To date geoengineering appraisals have employed narrowly framed inputs (such as context, options, methods and criteria) and 'closed' output reflexivity often amounting to unitary and prescriptive policy recommendations. For the first time, in this paper we begin to address these limitations by 'opening up' appraisal inputs and outputs to a wider diversity of framings, knowledges and future pathways. We use a Multi-Criteria Mapping methodology to appraise carbon and solar geoengineering proposals alongside a range of other options for responding to climate change with a small but diverse group of specialists and stakeholders. Overall option rankings are found to vary considerably between participant perspectives and criteria. Despite these differences, the ranks of geoengineering proposals are most often lower than options for mitigating climate change (including voluntary behaviour change and low carbon technologies). The performance of all options is beset by uncertainty, albeit to differing degrees, and it can often be seen that better performing options are outperformed under their pessimistic scores by poorer performing options under their optimistic scores. Several findings contrast with those of other published appraisals. In particular, where stratospheric aerosol injection has previously outperformed other geoengineering options, when assessed against a broader diversity of criteria (spanning all the identified criteria groups) and other options for responding to climate change it performs relatively poorly. We end by briefly exploring the implications of our analysis for geoengineering technologies, their governance, and appraisal.

1. Introduction

Resurgent interest in the prospect for 'geoengineering' the climate follows a long history of desire to bring the forces of nature under human control (Fleming, 2010). Once believed to be powers that only the Gods of ancient mythologies and religions could bestow, the ideas of climate control are now thought to be within the reaches of science and technology. Research into climate modification reached its height during the Cold War, where plans to 'optimise' climate (e.g. Rusin & Flit, 1960) were succeeded by experiments to weaponize weather during the Vietnam War (Fleming, 2006). Today such research is concerned with tackling anthropogenic climate change through geoengineering, an idea that gained prominence in 2006 when Nobel laureate Paul Crutzen, frustrated by insufficient mitigation efforts, proposed artificially enhancing the Earth's albedo through stratospheric aerosol injection (Crutzen, 2006). Geoengineering comprises a disparate collection of deliberate, large-scale interventions in the Earth's climate system that can broadly be divided amongst 'carbon geoengineering' proposals which seek to remove and sequester atmospheric CO_2, and 'solar geoengineering' proposals which seek to increase the reflection of sunlight away from the Earth (Royal Society, 2009). Together with the risk of climate 'emergencies' and other normative rationales for geoengineering concerted efforts have begun to appraise the pros and cons of these different proposals, in order to provide critical decision support to policy makers around the world.

A recent review of existing geoengineering appraisals reveals that they hold a number of significant limitations relating to their narrowly framed inputs and 'closed' output reflexivity (Bellamy *et al.*, 2012). Appraisals of geoengineering have been conditioned by narrow problem framings, in which particular issues, such as the predominant 'insufficient mitigation' (e.g. Crutzen, 2006) and 'climate emergency' (e.g. Blackstock *et al.*, 2009) frames, exclude alternative problem definitions. Concurrently, appraisals have almost exclusively focused on assessing single geoengineering options (e.g. Keith *et al.*, 2005; Lampitt *et al.*, 2008; Robock *et al.*, 2009) or on developing internal comparisons between geoengineering options (e.g. Keith, 2000; Lenton & Vaughan, 2009; NERC, 2010). Existing appraisals have thus consistently isolated geoengineering proposals from their decision context by omitting the wider portfolio of options for responding to climate change, spanning mitigation and adaptation.

Methods for appraising geoengineering have most often closed down around 'expert-analytic' procedures such as computer modelling (e.g. Moore *et al.*, 2010), cost-benefit analysis (e.g. Bickel & Lane, 2009), expert review (e.g. Robock, 2008) and multi-criteria analysis (e.g. Boyd, 2008), and employed technical criteria such as those spanning efficacy, feasibility and economics (Bellamy *et al.*, 2012). While such methods make a vital contribution to the appraisal of technical issues and in building an essential knowledge-base for geoengineering governance, they do not adequately respond to the 'post-normal' scientific context in which geoengineering resides (Funtowicz & Ravetz, 1993). The high uncertainties and high stakes of climate change, heightened further by its intentional manipulation through geoengineering, limit the propriety of 'normal' basic or applied science. These uncertainties and stakes demand that appraisals include axiological factors, not only from experts but from all those with a stake in the issue, from an 'extended peer community'.

Inputs to appraisals of geoengineering, such as perspectives, procedures, options and criteria, have been found to be narrow in focus (Bellamy *et al.*, 2012). These often unacknowledged instrumental framings can exert significant power upon appraisal outputs, 'closing down' around those particular knowledges and marginalising the true diversity of perspectives that bear upon the issue (Stirling, 2008). Following on from this, there has been a tendency for the outputs, such as findings, conclusions and recommendations, from many of the aforementioned appraisals of geoengineering to have been closed down as well. This can lead to unitary and prescriptive decision support, and overlook the diversity and sensitivities of decision pathways that are available, possible or imaginable (Stirling *et al.*, 2007).

Ultimately these contextual, methodological and un-reflexive instrumental framings have amounted to the closing down upon particular values and assumptions, whilst excluding the diversity of others. In many cases, it has led to conclusions that close down upon particular options, principally stratospheric aerosol injection: a controversial solar geoengineering proposal to inject reflective sulphate particles into the stratosphere and cool the Earth (e.g. Keith, 2000; Lenton & Vaughan, 2009; Izrael *et al.*, 2009). Such closure in 'upstream' technologies such as geoengineering can risk premature 'lock-in' and conflict between divergent values and interests, as was previously the case with the proposed commercialisation of genetically modified (GM) crops (Wilsdon & Willis, 2004).

Methods of appraisal exist which actively seek to address issues of closure such as those pervading appraisals of geoengineering, by 'opening up' to the wider diversity of framing conditions and perspectives that permeate the issue. These include, but are not limited to, scenario workshops (Ogilvie, 2002), Q-method (McKeown & Thomas, 1988), Stakeholder Decision Analysis (Burgess, 2000) and Deliberative Mapping (Burgess *et al.*, 2007). This article presents the findings of research using another such innovative methodology, Multi-Criteria Mapping (MCM) (Stirling, 1997; Stirling & Mayer, 2001), a multi-criteria option appraisal method designed to map the diversity of contrasting perspectives bearing upon complex policy issues.

This research on geoengineering builds on the successful development and application of MCM in the anticipatory appraisal of analogous complex and uncertain emerging technologies, including agricultural biotechnologies (Stirling & Mayer, 2001), medical health technologies (Davies *et al.*, 2003), and energy-related technologies (Stirling, 1994; Chilvers and Burgess, 2008). Whilst acknowledging other possible framings, such as climate optimisation or weaponization the research sought to appraise carbon and solar geoengineering proposals using the broader framing of 'responding to climate change' and the diverse portfolio of alternative options it opens up. This was done with a range of specialist and stakeholder perspectives, as part of a wider research project also involving public participation.

2. Methods

As with other multi-criteria methods, the MCM method comprises four stages: (1) developing a set of options to appraise; (2) characterising a range of criteria against which to assess those options; (3) scoring the relative performance of the options against those criteria; and (4) assigning a weighting to each criterion to indicate their relative importance. The procedural methods of the MCM method are explained more fully in Stirling and Mayer, (2001), but aspects specific to this study demand detailed discussion here.

2.1 Framing

In recognising the narrow contextual limitations of earlier appraisals of geoengineering, the study adopted an open problem framing and broad decision context. Rather than defining the 'problem' as a leading one of 'insufficient mitigation' or the risk of a 'climate emergency', for example, it was framed as an exercise in 'responding to [global] climate change' which allowed for a diversity of perspectives to bear upon it. This problem framing extended to the adopted decision context, where geoengineering proposals were presented alongside alternative options for responding to climate change; as well as allowing for the introduction of additional options defined by the participants themselves.

Options for responding to climate change can be broadly divided amongst mitigation, adaptation and geoengineering strategies. The Intergovernmental Panel on Climate Change (IPCC) defines *mitigation* as 'implementing policies to reduce greenhouse gas emissions and enhance sinks' (IPCC, 2007, p84). The inclusion of sink enhancement in this definition reflects some ambiguity relating to the categorisation of carbon geoengineering proposals, some of which share this aim. In this study we disaggregate them and restrict mitigation to mean options available to reduce greenhouse gas emissions, spanning energy conservation/efficiency and low carbon energy production.

The IPCC defines *adaptation* as '…measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects' (IPCC, 2007, p76). The objectives of adaptation, however, are fundamentally different to those of geoengineering and mitigation. Whilst those latter strategies seek to avoid or lessen climate change itself, adaptation seeks to address its impacts. Adaptation options are responses to temporally and spatially specific impacts, experienced as weather events, and therefore cannot be presented alongside geoengineering and mitigation options at a meaningful resolution. For example, stratospheric aerosol injection and offshore wind energy both seek to tackle or avoid climate change, but constructing flood defences does not. Whilst adaptation strategies could not be meaningfully included in the study as discrete options to appraise, the concept of adaptation and of adaptive capacities would be implicitly addressed through the inclusion of a baseline 'business as usual' option and its resultant climatic impacts.

A review of options for responding to climate change yielded an extensive range of potential options for inclusion within the study. For practical reasons these options could not be presented for appraisal in their entirety, and so the options were screened against a range of criteria in order to produce a list of discrete options to appraise that were indicative of the diversity of options available. These criteria assessed the diversity of: (1) strategies (geoengineering or mitigation, technological or non-technological, engineered or natural); (2) likely governance (territorial or commons-based operation, centralised or distributed control); (3) policy instruments (regulatory, market-based or voluntary); and (4) novelty/maturity (novel/immature or established/mature). The review yielded seven 'core' options to be appraised by all participants in the study and seven 'discretionary' options to be appraised by participants at their discretion (see Table 1). Options were necessarily presented at different scales of impact and none were presented as 'silver bullets' capable of tackling climate change in isolation.

Table 1. The definitions of 'core' options (C1 – C7) appraised by all participants and 'discretionary' options (D1 – D7) appraised by some participants at their discretion.

Option	Definition
C1 Voluntary low carbon living	Promoting voluntary reductions in domestic and commercial energy use.
C2 Offshore wind energy	Increasing the proportion of energy provided by offshore wind turbines.
C3 New market mechanism	Developing a new and expanded market-based carbon trading mechanism.
C4 Biochar	Focusing research and development into the production of biochar and its application to soils.
C5 Air capture and storage	Focusing research and development into the use of technology for capturing CO_2 from the ambient air.
C6 Stratospheric aerosol injection	Focusing research and development into the injection of reflective sulphate particles into the stratosphere.
C7 Business as usual	Continuing with business as usual, with no further adoption of options for responding to climate change.
D1 Nuclear fission energy	Increasing the proportion of energy provided by nuclear fission power stations.
D2 Coal energy with CCS	Focusing research and development into the use of technology for capturing CO_2 at source from coal power stations.
D3 Carbon tax	Increasing and widening taxation of CO_2 emitted during the fuel cycle.
D4 Nuclear fusion energy	Focusing research and development into the use of nuclear fusion for energy generation.
D5 Iron fertilisation	Focusing research and development into the application of iron to the ocean to stimulate algal growth.
D6 Cloud albedo enhancement	Focusing research and development into the use of technology to enhance cloud reflectivity.
D7 Space reflectors	Focusing research and development into the use of reflective mirrors in Earth orbit.

Acronyms: carbon capture and storage (CCS).

2.2 The participants

A diverse group of twenty-four specialists and stakeholders were identified by the research team to participate in a series of scoping interviews. Interviewees were identified for their seniority and appreciation of the international context of climate change, and their diversity of perspectives in relation to their: (1) working sector (academia, civil society, industry or government); (2) disciplinary specialism's (natural or social science perspectives relating to general or specific geoengineering proposals or mitigation options); and (3) personal attitudes to geoengineering research (arguments pro or contra geoengineering research as mapped by Betz & Cacean [2012]). Interviewees were screened against these criteria in more depth during a short telephone interview, culminating in the recruitment of twelve diverse specialists and stakeholders who would go on to participate in the full MCM study (see Table 2).

Table 2. The participants.

Code	Position	Expertise	Perspective†
A	Environmental social scientist	M	A9(-); A73(-)
B	Interdisciplinary climate scientist	M, A, G	A32(+); A52(-); A58(-); A75(-)‡
C	Earth system scientist	G	A32(+); A87(+)
D	Science and technology social scientist	G	A32(+)
E	Volcanologist	G	A32(+); A87(+)
F	Int. conservation charity manager	M, G	A32(+)
G	Int. technology action group manager	G	A9(-); A73(-)
H	Int. commercial competition manager	G	A32(+)
I	Nat. engineering institution manager	M, G	A32(+)
J	Nat. government civil servant	G	A32(+); A87(+)
K	Local government public sector officer	M, A	A32(+)
L	Nat. government scientific advisor	M, A, G	A32(+); A87(+)

Acronyms: international (Int.); national (Nat.); mitigation (M); adaptation (A); geoengineering (G). Notes: † perspective on geoengineering research elicited during scoping interviews. Perspectives coded against argument map by Betz & Cacean (2012). Arguments denoted as pro (+) or contra (-) geoengineering research: mitigation obstruction (A9); insufficient mitigation (A32); irreducible uncertainty (A52); socio-political uncertainty (A58); technical fix (A73); hubris (A75); preparing informed decision (A87). ‡ Participant B pro researching select carbon geoengineering proposals complementary to mitigation, contra large scale solar geoengineering.

2.3 The interviews

Prior to interview participants were given a booklet detailing the aims and methods of the study, together with definitions of the 'core' and 'discretionary' options to be appraised. Participants were then interviewed on a one-to-one basis at their place of work using the computer software program 'Multi-Criteria Mapper'. The principal researcher guided each participant through the four stage multi-criteria process detailed above, in interviews that lasted between one and three hours. A second set of interviews took place several weeks later in order to present participants with the initial results of the study and to further explore their views in relation to geoengineering appraisal and governance as well as to reflect on their participation in the study.

2.4 Analytical methods

The MCM study produced a variety of quantitative and qualitative data outputs. The quantitative data consisted of 'optimistic' and 'pessimistic' scores of option performance given by each participant (taken together as a quantification of uncertainty), and criteria weightings. These data allowed for the production of aggregate scores of option performance rank, calculated using a simple linear additive weighting aggregation model: $R_i = \Sigma_c S_{ic} \cdot W_c$ where overall performance rank for a given option (R_i) is the sum of performance scores for that option under a given criterion (S_{ic}), multiplied by the corresponding criterion weighting (W_c) (see Stirling & Mayer, 1999). A 'real-time' sensitivity analysis was performed during the interview to assess the effects of different criteria weightings on overall option rankings. Each participant concluded with satisfaction that their chosen weightings accurately represented their perspectives. A second sensitivity analysis was conducted to assess the effects of ranking aggregate optimistic and pessimistic scores on overall rank order, which were found to change very little.

The MCM interviews also produced in-depth qualitative data of the key reasonings, meanings and considerations of all participants in relation to: the overall framing of the problem and options for responding to climate change; the criteria and principles against which the performance of options was judged; the judgements made in scoring the options against criteria; weighting considerations; and reflections on the appraisal process and implications for geoengineering governance. All interviews were audio recorded, fully transcribed and subject to coding analysis using the qualitative data analysis software program Nvivo. As part of this process criteria and principles were coded first into emergent sub-groups of related issues, and second into emergent overall groups of related sub-groups. The reasonings underpinning judgements of option performance against each criterion were then explored in the analysis.

3. Results and discussion

3.1 Options and criteria

In addition to the seven core options, ten participants opted to appraise discretionary options, with two participants appraising all seven of them. Seven participants introduced a total of nine 'additional' self-defined options for appraisal. Four of these were carbon geoengineering proposals, two of which were variants of air capture and storage. Another four were approaches to mitigation, and one was a broader 'cultural transformation', to which responding to climate change was considered a co-benefit.

The participants developed a rich diversity of criteria to appraise options for responding to climate change. A total of 61 criteria were developed, which have been coded into 26 emergent subgroups that form part of 8 main criteria groups (see Table 3). The criteria developed in interviews addressed issues spanning, and often transcending, the natural, applied and social sciences, ranging from issues of efficacy and environment, to issues of feasibility and economics, to issues of politics, society and ethics.

Whilst the criteria may appear discrete, the participants recognised that each of their criteria represented a complex aggregation of issues and often bore close relations to other criteria.

A total of 23 'principles' were also developed and subsequently classified into 18 emergent subgroups which map onto the same 8 groups of the criteria (see Table 3). 15 of the subgroups were developed initially as criteria but later repeated as separate principles to rule out options deemed unacceptable. The remaining 3 were developed purely as principles, regarding issues of governance, human impacts and intergenerational equity.

Table 3. Classification of criteria and principles into groups and subgroups.

Groups	Subgroups
Economic	Commercial viability; cost†; cost effectiveness; economic sustainability; public investment
Efficacy	Climate change impacts reduction†; climatic response time†; efficacy of intended effects; global temperature reduction†; greenhouse gas reduction†
Environmental	Environmental impacts†; environmental side effects†; transboundary impacts†
Ethical	Distributive justice†; ethical questions; intergenerational equity‡; ownership and control†
Feasibility	Development time; state of knowledge; technical feasibility†; resource availability
Political	Political acceptability†; political viability; governance‡
Social	Cultural acceptability; human impacts‡; social acceptability†; socioeconomic impacts†
Other	Co-benefits†

Notes: all listed are criteria except where † indicates corresponding criterion also used as a principle; ‡ indicates a principle. In cases where a criterion overlapped with another, the aspect emphasised during the interview was used to categorise the criterion.

3.2 Scoring of option performance

3.2.1 Efficacy

Of the core geoengineering options, the efficacy of stratospheric aerosol injection was the most variable. This was in part a reflection of what participants' deemed to be the 'objective' at stake, be it temperature reduction, greenhouse gas reduction or otherwise, culminating in a variety of different efficacy criteria. Participants concerned with a reduction in global temperature (A, E, K, L) or a rapid climatic response time (E) scored the option very highly, with one participant describing it as 'alarmingly easy' (E). The high scores were accompanied by caveats relating to potential difficulties in achieving globally uniform temperature changes. Unsurprisingly, participants concerned with a reduction in greenhouse gases (B, G, J) scored the option very poorly, citing the option's failure to address CO_2 emissions or concentration and the associated problem of ocean acidification. The option was ruled out against efficacy principles by participants A and G. This variability is in stark contrast with other appraisals' consistent claims of high efficacy (e.g. Izrael *et al.*, 2009; Lenton & Vaughan, 2009; Royal Society, 2009).

The efficacy of air capture and storage was also highly variable, but it scored moderately overall. Whilst participants expressed confidence in people's willingness to invest in the technology, much of the uncertainty stemmed from its perceived technological immaturity. Participants cited its feasibility in principle, but raised doubts as to its potential performance at scale owing to resource limitations for processing vast quantities of air and the availability of geological reservoirs for its storage aspect. The option's slow rate of effect and failure to address other greenhouse gases were also cited. These findings too contrast with the high performance rating given by the Royal Society (2009). Biochar performed poorly against efficacy criteria, with many participants citing significant resource and spatial limits to its potential scalability.

Of the core mitigation options, the efficacy of a new market mechanism was the most variable. Whilst generally seen to perform very highly under the assumption that it were successfully implemented through a global international agreement, the perceived likelihood of such an agreement being achieved coupled with an undervalued carbon price and high emissions quotas led to the option also scoring poorly. Participant G viewed the option's potential to reduce greenhouse gas concentrations so poorly as to rule it out on principle.

Offshore wind energy performed moderately, with relatively little variability. Although it was emphasised by participants that none of the options under scrutiny should be viewed as a panacea, it was often stated with particular attention to offshore wind energy. Its heterogeneous geographical potential, inherent intermittency of electricity supply and need for effective integration with a 'smart grid' were cited as key limitations to its reliability. The voluntary low carbon living option performed very poorly, with some variability. Its acute susceptibility to the 'collective action problem', the desire of people to maintain carbon intensive lifestyles, and different priorities of both individuals and nations were also cited. The potential efficacy of the option was seen to be highly unlikely, without 'regulation' (L) or a 'disaster' to prompt changes in behaviour (D).

Business as usual performed consistently very badly, with E, F, G and J ruling the option out on principle for its slow rate of effect, if any, and its failure to reduce greenhouse gas concentrations, global temperature and the impacts of climate change.

3.2.2 Environment

Of the core geoengineering options, biochar scored the most highly against environmental criteria. Whilst some variability was expressed with respect to the possibility of adverse environmental impacts if the option were used at scale, impacts were generally seen to be restricted to soil and air quality, localised and few in number. Air capture and storage also scored relatively highly against environmental criteria, albeit with a greater degree of variability. The risk of 'leaks' and destabilised geological reservoirs featured prominently in interviews, alongside environmental concerns relating to the acquisition of resources demanded over the option's lifecycle. On the other hand, participants noted its likely regulation, monitoring and 'switch off' controllability.

Described as an 'emergency measure' (E), stratospheric aerosol injection performed consistently very poorly against environmental criteria. A swathe of foreseeable and transboundary impacts were raised, including stratospheric ozone depletion; effects on global circulation and regional weather patterns; shifts in the Inter-Tropical Convergence Zone (ITCZ) threatening rainfall in sub-Saharan Africa and the Indian Monsoon; as well as unforeseeable side effects. These risks were often cited from the results of climate model outputs, which were themselves seen to be highly uncertain and conservative. Novel threats such as a 'termination problem', also outlined in Russell *et al.* (2012), whereby a sudden temperature rise in line with the previously masked atmospheric CO_2 concentration would follow a cessation of stratospheric aerosol injection, as well as the continued impacts of ocean acidification, were also cited. Concern over the 'irreversibility' (H) of many of these environmental risks and the potential 'tipping' (I) of Earth systems into alternate states was also raised. Participant G judged the environmental side effects of the option to be unacceptable, and ruled it out on principle.

The voluntary low carbon living option scored very highly against environmental criteria, with participants often expressing difficulty in thinking of any adverse effects. The inadvertent use of higher carbon goods through the pursuit of low carbon goods was cited as a limitation, as was the possible environmental impacts of using alternatives to carbon. Offshore wind energy also performed highly, with some variability. Risks to birds and marine life were raised alongside more serious concerns regarding the large quantities of infrastructure to be manufactured, deployed, maintained and decommissioned at scale.

A new market mechanism performed reasonably highly against environmental criteria, but with a high degree of variability. Whilst some viewed the option as relatively benign, many others raised the problem of 'perverse incentives' in which certain activities are encouraged, in this case reducing CO_2 emissions, but inadvertently increasing environmental degradation elsewhere through the impacts of incentivised alternatives.

Business as usual performed very poorly, with some variability. Participants acknowledged that the environmental impacts of business as usual, and of the resulting climate changes, would be severe, with participants G, J and K ruling the option out on principle. Participant B was more optimistic about adaptability than others. A particularly interesting discourse that emerged surrounding business as usual was whether it would perform better or worse against environmental criteria than stratospheric aerosol injection. Three distinct positions emerged, with one participant remarking that 'business as usual is never going to be a better option than geoengineering' (E); another that '...the risk is probably about the same' (I); and another that '…with stratospheric aerosols we're actually exacerbating the risks' (B). As well as reflecting uncertainty around the side effects of stratospheric aerosols, this also reflects a complexity of ethical positions relating to geoengineering as a 'lesser evil' as critiqued by Gardiner (2010).

3.2.3 Feasibility

Of the three core geoengineering options, biochar scored most highly against feasibility criteria, albeit modestly and with some variability. Whilst its local scale feasibility was cited, participants expressed potential spatial and practical difficulties in scaling up the operation. Without large scale field trials, it was said, these uncertainties would remain, reflecting sentiments made in Lehmann (2007). Air capture and storage scored highly in principle, with participants C and H noting that they had either held or indeed bought a flask of CO_2 that had been captured from the air. However, the option scored poorly in terms of its technological maturity and the fact that it had not been proven to work at scale. This finding contrasts with the recent US Government Accountability Office (GAO) report, which placed air capture and storage at Technology Readiness Level 3 (GAO, 2011). Limits to that scalability were also cited, with reference to the availability of geological reservoirs. Participant I proposed that this issue could be overcome through 'carbon recycling' rather than storage, through air capture with 'closed-loop utilisation'. However, this proposal would negate the option's negative emissions capabilities.

Stratospheric aerosol injection generally scored poorly against feasibility criteria, but with a considerable range of variability. As with air capture and storage, stratospheric aerosol injection was seen to be highly feasible in principle, but scored very poorly in its potential practice. This finding contrasts with the high engineering feasibility conferred in Fox & Chapman (2011). Whilst one participant commented that '… from a technical point of view I could do it tomorrow afternoon' (I); others cited potential difficulties in achieving the desired particle size and dispersion in the stratosphere, and that these difficulties would not be understood until field trialling had begun. Another participant (E) drew on recent experiences with the Stratospheric Particle Injection for Climate Engineering (SPICE) project, noting that aspects of feasibility that needed to be tested 'outside the lab' would be constrained not only by technical limitations but also social issues.

The voluntary low carbon living option scored relatively highly against feasibility criteria, with some variability. Participants viewed the option as very easy to do both technically and practically on an individual basis, but alongside the caveat that considerable social and economic barriers would constrain its feasibility at scale. Participant I denounced the option as being synonymous with business as usual, and ruled it out on principle. Offshore wind energy also scored relatively highly with some variability. The successes of existing and planned offshore wind energy projects were cited, but so too were maintenance and logistical difficulties in operating them at scale over their lifecycles.

A new market mechanism scored moderately, but with high variability relating to perceived slow development time, complexity at scale and perceived problems with securing an effective carbon price. Participant I noted that this latter issue could be addressed if the option were combined with a variant of air capture and storage which could be used to set the carbon price, as also outlined in Fox (2012), based on the financial cost incurred to 'correct' the economic externality.

Business as usual scored highly against feasibility criteria, much to participants' regret. Some variability was expressed, however, relating to resource limits associated with the unsustainable exploitation practices of business as usual; as well as a likely diminished feasibility under mounting social and political pressure.

3.2.4 Economics

Of the three core geoengineering options, the economics of stratospheric aerosol injection was the most variable. The option's performance depended upon what was included in its base cost, which if considered purely in terms of the resources required to operate stratospheric aerosol injection, it scored very highly. One participant commented:

'...it's terrifyingly good value for money... just purely on a technological delivery basis it's probably on the order of around a billion dollars' (E).

However, if the base cost included potential economic costs incurred by adverse side effects, it scored poorly. Participants cited the potential need for compensating regions that suffered adverse impacts, as well as the on-going costs associated with a reliance on stratospheric aerosol injection in order to avoid the termination problem. These findings would suggest that the economics of stratospheric aerosol injection are not 'incredible' after all, confirming conjecture by Robock (2008) and conflicting with other consistently favourable claims (e.g. Barrett, 2008; Bickel & Lane, 2000; Keith & Dowlatabadi, 1992; Keith, 2000; Levi, 2008).

Biochar performed moderately against economic criteria, but with a degree of variability. Its economics were seen to depend greatly on the scale at which it would be applied, with larger scale operations seen as increasingly expensive. Participant H noted viable economic markets open to biochar, but cited difficulties in securing sales and investment being experienced by existing companies. Air capture and storage performed poorly against economic criteria, with some variability associated with potential technological breakthroughs, different technology designs and wildly contrasting estimates of cost/tonne of CO_2 captured communicated by air capture proponents and their critics. The overall poor performance contrasts sharply with the possible 'appraisal optimism' (Flyvjberg et al., 2003) of proponents (e.g. Keith *et al.*, 2005). On the other hand, the option was seen to lend itself to private commercial pursuits, but given the quantities of air that needed to be processed, together with a legacy of infrastructure, maintenance and storage costs, it was viewed as unlikely to ever be cheap.

Of the three core mitigation options, the voluntary low carbon living option scored most highly. Most participants viewed the option favourably as it would not be adopted unless it was affordable. Higher level costs, however, such as running a social marketing campaign were viewed as potentially greater, given their need to compete with the greater marketing budgets of business as usual. A new market mechanism also scored highly, but with some variability. It was noted that its very premise was to be economically efficient, but that existing market mechanisms had suffered from a 'chronically undervalued' (E) carbon price. On the other hand, it was seen to be beneficial for stimulating innovation, and by extension the economy, through new markets and businesses.

Offshore wind energy scored moderately against economic criteria, with some variability surrounding the policy framework in which it would operate. Considerable costs associated with the legislative planning, installation, grid connection, maintenance and decommissioning of offshore wind turbines were cited as reasons for concern alongside high electricity costs passed on to consumers. Despite these reservations, participants noted that achieving economies of scale, future investment and technological advancements would likely reduce these costs.

Business as usual performed poorly against economic criteria, with participants noting its beneficial generation of economic activity, but extensive unintended costs. Participant F deemed the costs that would be incurred to the world by climate change though pursuing business as usual 'would be off the scale', and ruled the option out on principle.

3.2.5 Politics

Of the three core geoengineering options, biochar performed the most highly against political criteria. Participants cited its politically attractive 'win-win sales talk' (C) and the fact that it is already practiced, albeit on a small scale. However, some variability was expressed when considering the option's performance at larger scales of deployment, where more people would be affected by its use. Air capture and storage also performed highly against political criteria. Whilst participants cited no need for multilateral agreements for its use and its compatibility with commercial uptake, politically sensitive risk issues were noted surrounding the siting and safety of carbon storage facilities.

Stratospheric aerosol injection scored very poorly against political criteria. It was seen as an incredibly difficult political issue, even under a best-case scenario where multilateral negotiations would be pursued. Participants expressed significant doubts about its viability, given the diverse cultural and vested interests that have confounded existing attempts to secure a global agreement to mitigate. The fact that no legal framework or governance structures are in place gave rise to concerns over the risk of unilateral deployment, reflecting those aired by the Solar Radiation Management Governance Initiative (SRMGI, 2011). One participant commented that 'In terms of international law, it's a black hole' (C). The global risks that might arise from such an endeavour raised issues of geopolitical tensions and of the need for compensation mechanisms to recompense regions that suffered adverse impacts. Participant K considered stratospheric aerosols to be politically unacceptable, and ruled the option out on principle without sufficient governance to control it.

Offshore wind energy scored the most highly of the three core mitigation options. It was cited as being politically more acceptable than its onshore counterpart, notwithstanding aesthetic objections from coastal communities. The voluntary low carbon living option performed moderately against political criteria, with participants citing its voluntary nature as unlikely to generate political tensions. Concurrently, the option was criticised for lacking political leadership and drive, as well as potential regulation.

A new market mechanism scored moderately against political criteria, but with a high degree of variability. Whilst the option was viewed favourably in that it would not affect citizens in any visible way, difficulties surrounding the willingness of different nations to participate were seen as unlikely to lessen. Participant F also raised the contested issue of historical emissions and the burden of responsibility.

Business as usual scored highly against political criteria. Much as with its performance against feasibility criteria, it was with participants' regret that change was politically undesirable.

3.2.6 Society

Biochar scored reasonably highly against social criteria, with some variability. Its well established use, potential improvements to agricultural yields and publically perceived 'naturalness' were all viewed as positive aspects of biochar. These findings lend support to the positive public perceptions recorded in the NERC (2010) Experiment Earth? dialogue. However, participants often cited the potential for land-use conflicts with biochar practiced on larger scales, and a number of vocal oppositional non-governmental organisations. Air capture and storage scored moderately, with some variability associated with its safety and its aesthetic value. Public fears of sudden CO_2 release were expressed, citing the 1986 Lake Nyos outgassing as an analogy (BBC, 1986). Participants often used onshore wind turbines as an analogy for the aesthetics of air capture and storage, noting the risk of potential 'NIMBYism' (Gipe, 1995).

Stratospheric aerosol injection scored very poorly against social criteria, with variability relating to its very premise, distribution of effects and deployment. In its best case participants said the option mirrored a natural system, that of a volcanic eruption. Participant E remarked that 'Stratospheric aerosol injection rightly scares the [expletive] out of everybody'. Participant L commented that the very idea was likely to be met with public hostility, whilst participant E cited a 'reluctant acceptance'. This latter view finds resonance in recent public engagement research (Macnaghten & Szerszynski, 2013) and more specifically, with the SPICE project (Parkhill & Pidgeon, 2011). The social inequities risked by an uneven distribution of the option's effects were raised often by participants, citing secondary impacts of environmental risks. Strong opposition from non-governmental organisations was also cited, but participant K added that technological robustness and satisfactory governance could help mitigate concerns. Participants A and G judged the social acceptability and socioeconomic impacts of the option to be unacceptable, and ruled the option out on principle.

The voluntary low carbon living option performed highly against social criteria, as it was seen to be unforced and therefore acceptable. However, participants often noted the option's inherent conflict with people's lifestyles and their deep rooted practices, which would discourage its adoption. Participant K noted that many nations are already living low carbon lifestyles, so such a proposal would be unproblematic. Offshore wind energy scored highly against social criteria, but with some variability. As with the political criteria, it was cited as being more socially acceptable than its onshore counterpart. On the other hand, its cost of electricity to the consumer was cited as being expensive in the face of cheaper, but higher carbon, alternatives.

A new market mechanism scored moderately against social criteria, with some variability. As with the political criteria, it was viewed favourably in that it would not affect citizens in any visible way, but this differed greatly between nations. Participant G also raised concerns about the mechanism's potential for creating unfairly distributed socioeconomic impacts, citing existing Clean Development Mechanism (CDM) projects to develop biofuels. The extent of these risks was judged by that participant to be unacceptable, and they ruled the option out on principle.

Business as usual scored moderately against social criteria, but with some variability. The poverty alleviation brought about through business as usual was seen as socially beneficial, and public perceptions of the resultant climate change itself were viewed as conservative and therefore of limited social concern. However, participants argued that strong opposition from non-governmental organisations would impact, as would the increasingly apparent impacts of climate change. Indeed, the socioeconomic impacts over time were viewed by participant G to be unacceptable, who ruled the option out.

3.2.7 Ethics

Of the three core geoengineering options biochar performed most highly in relation to ethical criteria, scoring moderately with some variability. Its localised nature was seen by participants to be less troubling, even beneficial, compared to those options with global implications. However, biochar was said to potentially pose similar social and environmental risks to biofuels if used at scale, with the imposition of risks and benefits on certain people, and the large-scale reorientation of agricultural production. Air capture and storage performed poorly, with some variability. Ethical concerns were largely related to the option's storage aspect, citing safety aspects of the CO_2 storage. Whilst a 'waste product' was involved, participant D remarked, the option would be beset by similar problems as those experience by nuclear fission energy, with its radioactive waste. This lends support to the additional option of air capture and closed-loop utilisation separately proposed by participant I.

Stratospheric aerosol injection scored very poorly against ethical criteria, with very little variability. It was widely held to pose difficult and unpredictable ethical disputes. The issue of consent was deemed to be a core ethical consideration, reflecting concerns noted by Corner and Pidgeon (2010), with participant D remarking 'I don't envisage a set of circumstances in which you could ever get something that looked like consent, either informed and given, or assumed, in anything like a satisfying way'. The same participant also stated that the ethics of possible unilateral deployment '…are tantamount to war'. Participants A and G considered concerns over the option's ownership, control and distributed impacts to be unacceptable, and they ruled the option out altogether.

Of the three core mitigation options, the voluntary low carbon living option scored most highly, with some variability relating to its ability to reduce social inequalities. Participant A noted that the option could be socially progressive depending upon the specific approaches adopted, citing the potential of personal carbon allowances. On the other hand, participant B argued the option could prove socially regressive where policies such as the UK's Feed in Tariff are publically funded via subsidies, but its uptake is restricted to only those with capital to afford the photovoltaic cells.

Offshore wind energy performed moderately with respect to its creation of industry and jobs, but some variability was expressed around its uneven imposition upon people. The option's high energy prices were viewed to be socially regressive. A new market mechanism performed poorly against ethical criteria. It was argued to raise a significant set of ethical questions around the new sets of 'winners' and 'losers' it would create.

Business as usual performed poorly against ethical criteria, albeit with some variability. Participant D noted that the ethics of 'carrying on' were unproblematic, as were those of its 'unintentional' impacts. Participant B stated that whilst business as usual was likely to be reducing global inequalities in absolute terms, there were considerable variations within and between countries. Participant G considered the prioritised interests of business over other considerations, including intergenerational equity, as unacceptable, and ruled the option out on principle.

3.2.8 Co-benefits

This 'other' criterion was appraised in isolation by only participant B, but themes of co-benefits were seen to run throughout the other participants transcripts despite not having been explicitly addressed.

Of the three core geoengineering options, biochar performed most highly against the co-benefit criterion, scoring moderately through its co-benefits to agriculture, namely: improved soil conditioning; increased water retention and related lowered irrigation demands; and increased productivity and yields. Air capture and storage scored very poorly, with no co-benefits identified. In agreement with other research (Hulme, 2012), stratospheric aerosol injection scored very badly, with participant B remarking at its likely 'co-problems' if anything, including a possible contribution to ozone depletion.

Voluntary low carbon living was seen to perform moderately against the co-benefit criterion, with personal benefits cited. Offshore wind energy scored moderately too, with improved energy security and health co-benefits associated with air quality improvements following a departure from fossil fuel energy sources. A new market mechanism was viewed as spouting similar potential health benefits, but scored poorly with little else to offer.

Business as usual scored highly against the co-benefit criterion, with clear social benefits associated with economic growth and poverty reduction.

3.3 Option ranking

Figure 1 shows the final overall rankings of each participant's appraisal of the seven core options. A number of key findings can be identified, the most obvious being that participant's different perspectives have amounted to different option rankings. Despite these differences, the ranks of geoengineering options are most often lower than those of the mitigation options. There are a few exceptions to this pattern, with the opposite being true for participant I. Important nuances also emerge between the individual options. Of the core geoengineering options, at their best biochar and air capture and storage are often seen to outperform stratospheric aerosol injection, drawing a distinction between carbon and solar geoengineering options. Of the core mitigation options, at their best voluntary low carbon living and offshore wind energy are often seen to outperform a new market mechanism. Business as usual is almost consistently the worst performing option. Interestingly, its performance is not unlike that of stratospheric aerosol injection, reflecting debates recorded in the interviews about their similarities.

Bellamy, R., Chilvers, J., Vaughan, N. E. & Lenton, T. M. (2013) 'Opening up' geoengineering appraisal: Multi-Criteria Mapping of options for tackling climate change ***Global Environmental Change*** *23(5):926-937* **doi: 10.1016/j.gloenvcha.2013.07.011** Accepted 9 July 2013, Available online 12 August 2013
http://www.sciencedirect.com/science/article/pii/S0959378013001179

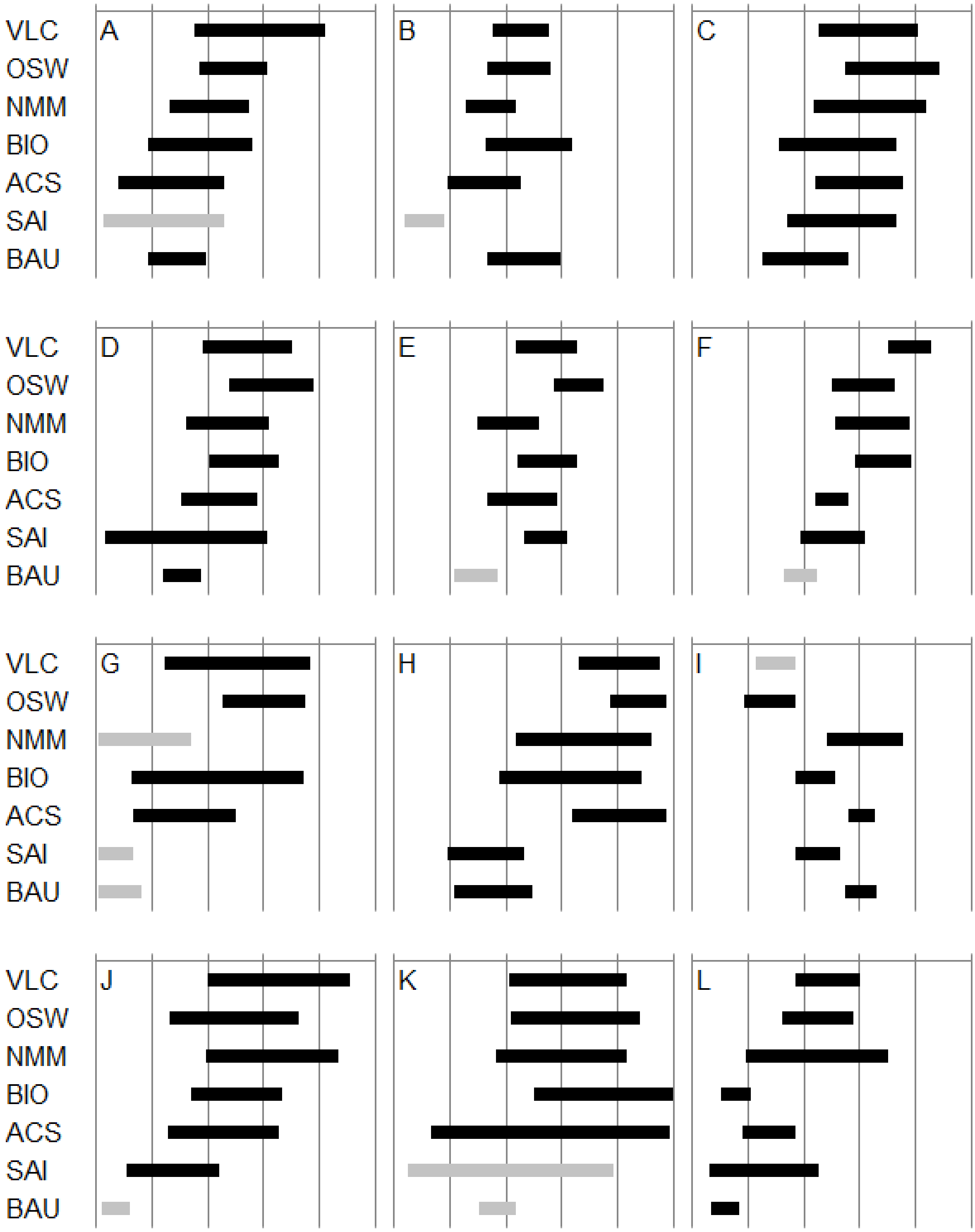

Figure 1. Final rankings of core options assigned by participants A - L. Acronyms: voluntary low carbon living (VLC); offshore wind energy (OSW); new market mechanism (NMM); biochar (BIO); air capture and storage (ACS); stratospheric aerosol injection (SAI); business as usual (BAU). Notes: performances increase on an arbitrary subjective scale to the right. Bar length represents uncertainty

between the mean optimistic and pessimistic performance scores across each participant's criteria. Greyed performance ranges indicate options ruled out against at least one principle.

The uncertainties represented by the ranges between optimistic and pessimistic scores are an important feature of the rankings. Indeed, it can often be seen that better performing options are outperformed under their pessimistic scores by poorer performing options under their optimistic scores. These uncertainty ranges echo the findings of earlier MCM research by Stirling and Mayer (2001), where GM crop options were appraised against non-GM alternatives. Levels of uncertainty varied widely across all options and participants, with some participants expressing more uncertainty with geoengineering options and some more with mitigation options. Uncertainty around business as usual was consistently relatively low, but its different rankings reflect different participant's perspectives as to its relative risks and benefits and of the adaptability of society. Participants representing government (J, K, L) could tentatively be described as having expressed greater uncertainty than the other sectors, contrasting particularly with participant I (industry).

Figure 1 also shows that three core options were ruled out against at least one principle by at least one participant. In fact, voluntary low carbon living and a new market mechanism were ruled out by 1 participant each; stratospheric aerosol injection was ruled out by 4 participants; and business as usual was ruled out by 5 participants. Table 4 details which options were ruled out, by how many participants, against which principles. Participants who did not rule any options declared that all options needed to be explored, with participant L remarking 'We can't afford to rule any of them out'.

Table 4. Options ruled out against which principles.

Option	Principles ruled out against
C1 Voluntary low carbon living (ruled out by 1 participant: I)	Technical feasibility
C3 New market mechanism (ruled out by 1 participant: G)	Greenhouse gas reduction; environmental side effects; transboundary impacts; socioeconomic impacts; ownership and control
C6 Stratospheric aerosol injection (ruled out by 4 participants: A, B, G, K)	Global temperature reduction; greenhouse gas reduction (2); environmental side effects; transboundary impacts; social acceptability; socioeconomic impacts; governance; political acceptability; distributive justice; ownership and control (2); co-benefits
C7 Business as usual (ruled out by 5 participants: E, F, G, J, K)	Climate change impacts reduction; climatic response time; global temperature reduction; greenhouse gas reduction (2); environmental impacts; environmental side effects; transboundary impacts; cost; human impacts; socioeconomic impacts; intergenerational equity; ownership and control
D5 Iron fertilisation (ruled out by 1 participant: G)	Greenhouse gas reduction; environmental side effects; transboundary impacts; socioeconomic impacts; ownership and control
D7 Space reflectors (ruled out by 1 participant: E)	Cost

Notes: (2) indicates a principle was invoked by two separate participants in relation to the corresponding option.

Figure 2 shows the aggregated final overall rankings of all participants' appraisals of core, discretionary and additional options. Whilst such aggregated rankings should always be interpreted with caution, the figure includes error bars to represent the extreme optimistic and pessimistic final overall scores of individual participants, to ensure that the full range of uncertainty is represented. Indeed, panel (a) shows the uncertainty to stretch almost the full length of the performance scale for many of the core options. The aggregated scores reaffirm the findings of the individual final overall appraisals discussed above and shall not be repeated here. It should be noted, however, that option ranks on panels b and c are not on the same scale as panel a, nor are they on the same scale as one another due to different participants and participant frequencies. They should therefore be interpreted with more caution.

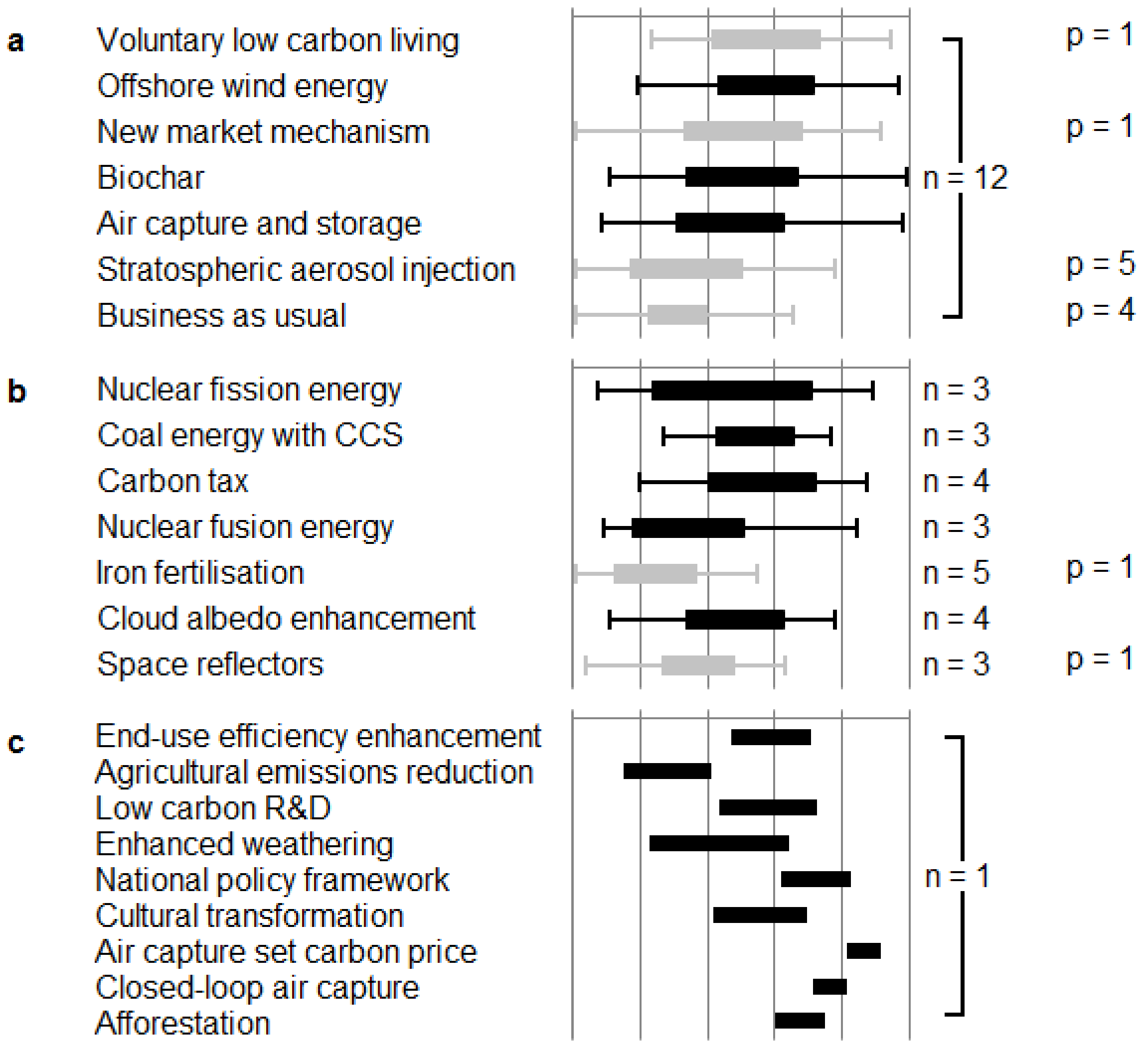

Figure 2. Aggregate final rankings of core options appraised by all twelve participants (panel a), discretionary options appraised by some participants (panel b, participant codes indicated beside corresponding options) and additional options appraised by individual participants (panel c, participant codes indicated beside corresponding options). Acronyms: carbon capture and storage (CCS); research and development (R&D). Notes: frequency of participants appraising (n) corresponding options and ruling them out on principle (p) indicated to the right of the graphic. Performances increase on an arbitrary subjective scale to the right. Bar length represents uncertainty between the grand mean of optimistic and pessimistic performance scores. Range 'error' bars represent extreme maximum and minimum mean optimistic and pessimistic scores. Greyed performance ranges indicate options ruled out against at least one principle by at least one participant. Note that options ranks on panels b and c are not on the same scale as panel a, nor are they on the same scale as one another due to different participants and participant frequencies. The relative positions of these ranking intervals are therefore much less robust than for the core options in panel a, and should be interpreted with caution.

Of the discretionary options (Figure, 2b), mitigation options can again be seen to outperform their geoengineering counterparts. Of the discretionary geoengineering options, at its most optimistic cloud albedo enhancement was seen to outperform space reflectors and iron fertilisation. Iron fertilisation was ruled out on principle by participant G for its questionable efficacy, risk of unintended environmental impacts, socioeconomic impacts, transboundary effects and privatised control. Space reflectors were ruled out on principle by participant E for their prohibitive financial cost. Of the discretionary mitigation options, at its most optimistic a carbon tax outperformed coal energy with carbon capture and storage and nuclear fission energy. Nuclear fission energy bore the most uncertainty, reflecting debates raised across the criteria. Nuclear fusion energy performed least well at its most optimistic, reflecting participants' pessimism over its development time or simply its viability.

Additional options (Figure 2c) were appraised by the individual participants that proposed them, often having been introduced as their favoured options. Indeed, five of these went on to outperform all other options being appraised by their proponent. These were cultural transformation (B); afforestation (E); air capture set carbon price and air capture with closed-loop utilisation (I); and end-use efficiency enhancement (L).

3.4 Implications for geoengineering governance and appraisal

This section further discusses the analysis with respect to the implications for geoengineering technologies, governance and appraisal, drawing on the reflections of the participants and with reference to the wider literature.

3.4.1 Geoengineering technologies 'in context'

There was strong agreement amongst participants that mitigation options should always be given priority over geoengineering proposals, which were viewed by participant C as an insurance policy. More precisely, carbon geoengineering proposals were seen as more acceptable than their solar counterparts, being potentially useful in offsetting emissions that proved difficult to mitigate against. The solar proposals were viewed by participant J only as a response to climatic emergencies such as those that might arise from climate tipping points. However, these generalised observations were joined by the fact that individual geoengineering proposals bore very little in common with one another and that the carbon-solar dichotomy, as well as the even more aggregated umbrella term 'geoengineering' was unhelpful. Such findings resonate with recent calls to disaggregate the term (Heyward, 2013; Boucher *et al.*, submitted).

3.4.2 Governance on a case-by-case basis

It was noted by all participants that no single regulatory framework would effectively govern the disparate suite of proposals that had been forced under the 'geoengineering' umbrella. Indeed, disaggregating the governance needs of the different proposals was described by participant D as '...going to be messy and complicated with a lot of twists and turns'. Participant B affirmed that the proposals would need to be governed on a case by case basis, remarking 'I can't offer a nice, neat set of principles'. It was noted that in many cases, established geoengineering proposals such as afforestation could be covered by existing governance structures. Participant C suggested that other existing governance structures could be modified and extended to cover other proposals, such as is the case with iron fertilisation and the London Convention (IMO, 2007). Such broadly optimistic views resonate with Humphrey's (2011) whilst contrasting with the more cautious Virgoe (2009). On the other hand, more difficult and novel governance issues were noted to arise from solar geoengineering proposals, in particular stratospheric aerosol injection (see also Macnaghten & Szerszynski, 2013). Transboundary effects and geopolitical relations were seen to be key points of contestation. Existing geoengineering governance projects such as the SRMGI (SRMGI, 2011) and the Oxford Principles (Rayner *et al.*, 2013) were said to be 'pushing in the right direction' (D).

3.4.3 Experimentation, demonstration and anticipation

Participants E and I both expressed their beliefs that geoengineering field trials would be likely in coming years. Both referenced the recent and controversial iron fertilisation experiments conducted by Canadian scientist Russ George (Lukacs, 2012), suggesting that trials of stratospheric aerosol injection would soon follow. Indeed, participant I even suggested that such trials could take place in the US by the mid 2020's, perhaps in response to extreme weather events, with other nations likely to follow suit. Whilst participant I remarked that effective governance arrangements were unlikely to be ready in time for such trials, participant E suggested that there would be swift moves to resist them. Participant L communicated the essential need for geoengineering governance structures to be in place before full-scale deployment was considered, and preferable need even before small-scale field trials. These comments echo the call for 'governance before deployment' in the Oxford Principles (Rayner *et al.*, 2013).

3.4.4 Multilateralism, unilateralism and scale

A dichotomy of governance implications emerged around those geoengineering proposals that would operate locally within nation states and those that would operate globally and internationally. The former group of proposals were considered to be largely unproblematic, falling under the jurisdiction of territorial governance regimes. The latter group of proposals, however, were viewed as requiring multilateral agreement sought through a global institution, most likely the United Nations (UN), echoing research by Virgoe (2009). Several participants noted the irony of this pursuit, with participant L remarking: 'it could take as long as the climate negotiations themselves'. Negotiating the terms of such an agreement, such as what temperature to set the 'global thermostat' were seen as intractable issues. Whilst participants noted that multilateral agreement should be sought for those geoengineering proposals with global, international implications, the risk of unilateral or consortia-led deployment remained. Stratospheric aerosol injection was of particular concern in this regard: 'We keep moving very quickly towards the SRM [Solar Radiation Management] conversation, because that's where the danger is' (F). The geopolitical tensions that could arise from such an endeavour were considered a matter of acute concern.

3.4.5 Inclusion, reflexivity and appraisal

Participant A emphasised the need for engaging publics in decision making on geoengineering, expressing its need to be open, democratic and accountable. They furthered the notion of reflexive governance, of the need for cautious and continuous appraisal, including beyond its eventual deployment should it happen. Such sentiments resonate with the objectives of real-time technology assessment and anticipatory governance (Guston & Sarewitz, 2002); of which reflexive appraisals processes such as MCM can form an important part. On this final point, in reflecting on their experience of the MCM study, all of the specialists and stakeholders remarked at the heuristic utility of MCM in mapping the extensive scope of issues raised by geoengineering. Indeed, the resultant complexity was considered 'difficult' to engage with by four participants. On the other hand, three others found the process 'logical' and 'straightforward'. The systematic rigor of the process, its flexibility to different participants' engagements and its openness to diverse framings and perspectives were all cited as strengths.

4. Conclusions and recommendations

In this study we have begun to address the limitations that have beset other appraisals of geoengineering by 'opening up' appraisal inputs and outputs to a wider diversity of legitimate framings, knowledges and future pathways that exist. In doing so a number of our findings contrast with those of other published appraisals which have adopted narrower inputs and closed down the outputs. In particular, where stratospheric aerosol injection has previously outperformed other geoengineering options, by opening up to a broader diversity of criteria (spanning all the identified criteria groups) and other options for tackling climate change it has been shown to perform relatively poorly. Under the broader framing conditions adopted in this study a further key finding is that geoengineering options most often performed less well compared to more established options for mitigating climate change (including voluntary low carbon living and offshore wind energy). As would be expected, these findings and the performance of all options are subject to varying degrees of uncertainty, something that is actively explored and transparently presented by the MCM approach.

In light of our findings, we propose three recommendations for policy and future research. First, no one option for tackling climate change is a panacea and policy should reflect the diversity of options and possible pathways at different scales. Second, our analysis illustrates that the term 'geoengineering' comprises a range of disparate technology proposals which have distinct qualities and performance ranges. This could be taken as support for calls to disaggregate the term and for geoengineering proposals to be governed on a case-by-case basis. There is certainly a need to discriminate between different proposals, their innovation contexts, and the imagined futures they invoke. Yet, the approach that we have developed in this paper cautions against moves to consider geoengineering proposals in isolation. Such practice would marginalise vital comparative dimensions and serve to close down the decision context. The key is to open up the framing of appraisals to consider geoengineering proposals in comparative context and avoid premature 'lock-in' to particular options or pathways. For those geoengineering proposals and appraisals that remain narrowly or technically framed the challenge is to reflexively consider the closing effects of their framing conditions (problem definitions, options, criteria, knowledge inputs, and so on) in a more open and transparent way.

Our third and final recommendation is that reflexive appraisal approaches such as MCM form an essential part of ambitions to realise wider frameworks of responsible innovation for geoengineering that encourage anticipatory, reflexive, inclusive and responsive forms of governing in the face of radical uncertainties/indeterminacies, competing visions and social concerns (Owen *et al.*, 2013; Stilgoe *et al.*, 2013; Macnaghten & Chilvers, 2013). Recent controversies relating to geoengineering experiments such as the UK's Stratospheric Particle Injection for Climate Engineering (SPICE) project (Macnaghten & Owen, 2011), the LOHAFEX (Iron Fertilisation Experiment) trial (Strong *et al.*, 2009) and the 'rogue' iron fertilisation of the Haida Salmon Restoration Corporation (Tollefson, 2012) stress the importance of the sort of *anticipatory* appraisal conducted in our research. The MCM process has been *reflexive* in the way it created spaces for scientists and stakeholders to openly reflect on and learn about their own framing conditions, assumptions, and the social, ethical and political implications of geoengineering technologies in a transparent way. While our approach has been *inclusive* in terms of specialist and interest group representation, it also provides opportunities to build on existing work exploring public deliberation on geoengineering technologies *per se* (e.g. Pidgeon *et al.*, 2013; Macnaghten & Szerszynski, 2013) by opening up to broader framings using MCM's sister-methodology of Deliberative Mapping (see Davies *et al.*, 2003; Burgess *et al.*, 2007; Chilvers and Burgess, 2008). The potential for reflexive appraisal approaches such as these to enhance the *responsiveness* of geoengineering governance depends on their connections with wider governance systems of which they are part. Such procedural techniques ultimately only form part of a diverse set of ways in which the reflexive and responsive capacities of actors and institutions implicated in governing geoengineering and climate change should be prompted and enhanced in collective-experimental, relational and ongoing ways (Wynne, 1993; Stirling, 2006; Chilvers, 2013; Stilgoe *et al.*, 2013).

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